REMARKS

This is a full and timely response to the non-final Official Action mailed **July 16, 2003**. A request for a one month extension of time and the requisite fee accompany this amendment. Reconsideration of the application in light of the above amendments and the following remarks is respectfully requested.

By the forgoing amendment, the specification and claims 7-9 have been amended. Additionally, claims 1-6 have been cancelled, and new claims 11-25 have been added. Thus, claims 7-25 are currently pending for the Examiner's consideration.

In the outstanding Office Action, the Examiner objected to the specification. This problem has been corrected by the present amendment, which includes a substitute specification. In preparing the substitute specification, the specification has been carefully reviewed for grammatical and idiomatic accuracy, and all needed corrections have been made. No new matter has been added.

Proposed corrections to the drawings have been filed concurrently as required by the Examiner. An explanation of the changes made in the drawings is provided above.

The Examiner rejected claim 7 under 35 U.S.C. § 112, first paragraph as not being enabled by the specification as originally filed. Claim 7 was filed in a preliminary amendment at the same time the present application as originally filed. Consequently, claim 7 contains originally-filed subject matter of the present application. To provide additional support for claim 7, the language of claim 7 has been added to the specification by the present amendment.

With regard to claim 7, the Office Action contends that a person of ordinary skill in the art would not be enabled to use a controller coupled to the image sensor to control a

display of two dimensional object scenes corresponding to the image data signals. Applicant respectfully disagrees. It seems clear that one of ordinary skill in the imaging art would possess knowledge sufficient to couple a controller to an image sensor to control display of a two dimensional object scene on the display as recited by independent claim 7. Accordingly, Applicant believes independent claim 7 to be clearly enabled one of ordinary skill in the imaging art as required by 35 U.S.C. §112, first paragraph.

The Examiner also rejected claims 7 under 35 U.S.C. §112, second paragraph as failing to provide sufficient antecedent basis for the recitation of "a controller coupled to the image sensor to control a display of two dimensional object scenes corresponding to said image data signals." The Examiner appears to be arguing simply that claim 7 is not supported by the specification as filed. As previously stated, claim 7 is an originally-filed claim of the present application and the language of claim 7 has been added to paragraphs10 and 37 of the specification. Accordingly, Applicant respectfully requests that this rejection under 35 U.S.C. § 112, second paragraph, be reconsidered and withdrawn.

The Examiner further rejected claims 8-9 under 35 U.S.C. §112, second paragraph. No specific language was mentioned with respect to claim 9. These claims have been carefully reviewed in light of the Examiner's comments and amended as necessary. Following this amendment, all the remaining claims are believed to be in compliance with 35 U.S.C. § 112 and notice to that effect is respectfully requested.

The Examiner rejected independent claim 10 under the judicially created doctrine of obviousness-type double patenting. The Examiner further stated that independent claim 10 would be allowable if a terminal disclaimer in compliance with 37 C.F.R. 1.321 (c) were to

be timely filed by applicant. A terminal disclaimer in compliance with 37 C.F.R. 1.321 (c) accompanies the amendment. Therefore, allowance of claim 10 is respectfully requested.

New claims 11-25 have been added. Support for claims 11-15 may be found in the specification, including paragraphs 1 and 26-35. Support for claims 15-25 may be found in the specification, including paragraphs 1 and 26-35 and in originally-filed claim 10.

For the foregoing reasons, the present application is thought to be in condition for allowance. Accordingly, favorable reconsideration of the application in light of these remarks is courteously solicited. If any fees are owed in connection with this paper which have not been elsewhere authorized, authorization is hereby given to charge those fees to Deposit Account 18-0013 in the name of Rader, Fishman & Grauer PLLC. If the Examiner has any comments or suggestions which could place this application in even better form, the Examiner is requested to telephone the undersigned attorney at the number listed below.

Respectfully submitted,

DATE: 14 November 2003

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METHOD AND APPARATUS FOR OMNIDIRECTIONAL THREE DIMENSIONAL IMAGING

FIELD OF INVENTION~~Field of Invention~~

[0001] This invention presents a set of methods and apparatus for omnidirectional stereo imaging. By "omnidirectional imaging system", we mean a system that is able to acquire images with a field-of-view covering the entire solid angle of a hemisphere (~~180 solid space angle~~2л steradians), simultaneously without any mechanical moving part. The field of view of a conventional camera or a light projector can be dramatically increased by employing a reflective mirror properly placed in front of the camera or the projector. A pair of omnidirectional cameras is able to form a unique stereo imaging system that is able to obtain three dimensional images of surrounding scene with 360 degree view angle. A combination of an omnidirectional camera and an omnidirectional structured light projector can also provide a means to obtain quantitative three dimensional measurements of the objects around the camera system. The omnidirectional three dimensional imaging methods and apparatus presented herein may offer unique solutions to many practical systems that need simultaneous 360 degree viewing angle and three dimensional measurement capability.

BACKGROUND ~~Prior Art Existing Approaches to Large FOV Imaging System~~

[0002] A number of approaches had been proposed in the past for imaging systems to achieve wide field-of-view (FOV). None of them, however, is able to generate 3D omnidirectional images. In the following paragraphs, we give a briefly survey on the state-of-the-art of current imaging systems that seek to achieve wide FOV.

~~Conventional Cameras~~

[0003] Most existing imaging systems employ electronic sensor chips, or still photographic film, to record optical image collected by ~~its~~ the imaging systems' optical lens system. The image projection for most camera lenses is modeled as a "pin-hole" with a single center of projection. ~~Since~~ The sizes of camera ~~lens~~ lenses and the imaging sensor have ~~their~~ practical limitations, such that the light rays that can be collected by a camera lens and received by the imaging device typically form a ~~corn with~~ cone having a very small opening

angle. Therefore, angular field-of-views for conventional cameras are within a range of 5 to 50 degrees. For example, an 8.5 mm F/1.3 camera lens for 1/2" CCD (Charge Coupled Device) chip only has an angular FOV of 41.2 degree.

~~Fish-Eye Lenses~~

[0004] Optical engineers had designed several versions of wide-viewing-angle lens system, called ~~the~~ fish-eye lenses ~~lens (see [1],[2])~~. See Wood, R.W., Fish-Eye View and Vision Underwater, Philosophical Magazine, 12 (Series 6):159-162, 1906; Miyamoto, K, Fish-Eye Lens, J. Optical Soc. America, 54(8):1060-1061, 1964. ~~The fish~~Fish-eye ~~lens~~ lenses ~~features~~ feature a very short focal length which, when used in place of conventional camera lens, enables the camera to view object for much wider angle (almost 2π steradians~~180 degree of hemisphere~~). In general, ~~the~~ a wider FOV~~,~~ requires a ~~the~~ more complicated design for the fish-eye lens ~~has~~. To obtain a hemispherical FOV, the fish-eye lens must be quite large in dimension, complex in optical design, and hence expensive. Also, it is very difficult to design a fish-eye lens that ensures single view point constraint, i.e., all incoming principal light rays intersect at a single point to form a fixed viewpoint. ~~This is indeed a problem with commercial fish-eye lenses, including Nikon's Fisheye-Nikkor 8-mm f/2.8 lens.~~ The use of fish-eye lenses for wide FOV imaging application has been advocated ~~by [3] and [4], among others~~. See Oh, S.J. and Hall, E., Guidance of a Mobile Robot Using an Omni-directional Vision Navigation System, Proc. SPIE, 852:288-300, Nov.,1987; U.S. Patent No. 5,359,363 issued to Kuban, D.P., et al, Oct.25, 1994. Although the acquired image by fish-eye lenses may prove to be good enough for some visualization applications, the distortion compensation issue has not been resolved~~, and~~. ~~the~~ The high unit-cost issues remain ~~to be~~ as major hurdles for its wide-spread applications. The fish-eye lens technique ~~has the advantage of adopting~~ adopts a statically positioned camera to acquire a wide angle of view. However the nonlinear property ~~resulted~~ resulting from the semi-spherical optical lens mapping ~~make~~ makes the resolution along the circular boundary of the image very poor~~,~~ ~~while~~. Further, the field of view corresponding to the circular boundary of the image usually represents a ground or floor where a high resolution of image is required.

~~Multi-Camera System or Rotating Imaging Systems~~

[0005] Large field of view of objects may be obtained by using multiple cameras in the same system, each ~~points towards~~ pointing in a different direction. However, issues ~~on~~ related to seamless integration of multiple images ~~is~~ are further complicated by the fact that each image produced by each camera has different centers of projection. The cost for such a system is usually high. The image processing required by multiple cameras or by rotating ~~camera~~ cameras in order ~~method~~ to obtain a precise information on position and azimuth of an object takes a long time, which is not suitable for real-time battle field modeling and reconnaissance applications.

[0006] Another straightforward solution to increasing the FOV is illustrated in Figs. 1A-1B. ~~of an~~ An imaging system (100) is ~~to rotate~~ rotated ~~the entire imaging system~~ about its center of projection (~~Figure~~ 110). An image sequence (120) of individual images (130) is acquired by the ~~camera~~ imaging systems at different positions are "stitched" together to obtain a panoramic view of the scene as seen in Fig. 1B. Such an approach has been recently proposed by several researchers. ~~(see [5], [6] [7]).~~ See Chen,S. E., QuickTime VR – An Image Based Approach to Virtual Environment Navigation, Computer Graphics: Proc. Of SIGGRAPH 95, 29-38, 1995; McMillam, L, and Bishop, G., Plenoptic Modeling: An Image-Based Rendering System, Computer Graphics: Proc. Of SIGGRAPH 95, 38-46, 1995; Zheng, J.Y., and Tsuji,S, Panoramic representation of scene for route understanding, Proc. 10 Int'l Conf. Pattern Recognition, 1:161-167, 1990. A very interesting approach developed ~~by [8]~~ that employs a camera with a non-frontal image detector to scan the world. See Krishnan, A, and Ahuja, N., Panoramic Image Acquisition, Proc. Of IEEE Conf. Computer Vision and Pattern Recognition (CVPR-96), 379-384,1996.

[0007] The first disadvantage of any rotating image system is that it requires the use of moving parts, and precision positioning devices. A more serious drawback is that such systems lack the capability of simultaneously acquiring images with wide FOV. Although such system can acquire precise azimuth information in omnidirectional view, the imaging process is time-consuming and the method is not applicable to real-time problems such as avoiding collision against moving obstacles or monitoring scene with mobile objects. This restricts the use of rotating systems to static and/or non-real-time applications.

[0008] In contrast, the present apparatus, ~~invention presented herein, called the omnidirectional camera,~~ is capable of capturing real-time omnidirectional images without

using any moving parts. By "omnidirectional images", we mean images with a field-of-view covering entire hemisphere (~~180 solid space~~ 2л steradians of solid-angle), simultaneously. ~~Figure~~ Fig. 2A-2B provides a comparison between fields of view of the present omnidirectional camera (200) ~~our Omnidirectional Camera~~, and those of panoramic (210) ~~camera~~ and conventional (220) cameras. As one can see, a panoramic camera is still not ommidirectional, since it can only provide a wide-angle of FOV at certain time instance~~,~~ Further, this FOV is not in all directions. On the other hand, the field of view of the omnidirectional camera (200) covers an entire hemisphere or 2л steradians of solid angle.

~~Summary of the Invention~~ SUMMARY

[0009] The primary objective of present invention is to provide a set of simple methods and apparatus to obtain simultaneously omnidirectional stereo images without using any moving parts. Accordingly, an improved imaging apparatus for generating a two dimensional image, includes a substantially hyperbolic reflective mirror configured to satisfy an optical single viewpoint constraint for reflecting a scene, an image sensor responsive to the reflective mirror and that generates two dimensional image data signals, and a controller coupled to the image sensor to control a display of two dimensional object scenes corresponding to the image data signals. The field of view of a conventional camera or a light projector can be dramatically increased by employing a reflective mirror properly placed in front of the camera or the projector. A pair of omnidirectional cameras is able to form a unique stereo imaging system that is able to obtain three dimensional images of surrounding scene with 360 degree view angle. A combination of an omnidirectional camera and an omnidirectional structured light projector can also provide a means to obtain quantitative three dimensional measurements of the objects around the camera system. The omnidirectional three dimensional imaging methods and apparatus presented herein may offer unique solutions to many practical systems that need simultaneous 360 degree viewing angle and three dimensional measurement capability.

~~Brief Description of the Drawing~~BRIEF DESCRIPTION OF THE DRAWINGS

[0010] ~~Figure 1 shows a conventional way to obtain panoramic images: the composition of multiple views of a rotated camera into a panoramic image.~~ Fig. 1A illustrates a sequence of multiple views taken by a rotated camera.

[0011] Fig. 1B illustrates the composition of multiple views of a rotated camera into a panoramic image.

[0012] ~~Figure 2 gives a comparison of the Field of View (FOV) among conventional cameras, panoramic cameras, and the proposed omnidirectional camera.~~ Fig. 2A illustrates the Field of View (FOV) of an omnidirectional camera.

[0013] Fig. 2B illustrates the FOV of conventional and panaromic cameras.

[0014] ~~Figure 3 provides examples of reflective convex mirror for Omni-Directional Imaging. Notice that these convex mirrors do not satisfy the single viewpoint constraint (SVC) condition: The (extension of) reflected rays do not meet at single viewpoint, i.e., the virtual viewpoint varies with rays' impinging location on the mirror.~~ Fig. 3A illustrates a conical mirror for omnidirectional imaging.

[0015] Fig. 3B illustrates a spherical mirror for omnidirectional imaging.

[0016] Fig. 3C illustrates a parabolic mirror for omnidirectional imaging.

[0017] ~~Figure 4 acquires Omni-Directional Image from the OMNI-Mirror. A video camera placed at location C can "see" objects in an entire hemisphere FOV, from a single virtual viewpoint at mirror's focal center O.~~ Fig. 4 illustrates an omnidirectional imaging system according to one exemplary embodiment.

[0018] ~~Figure 5 shows an embodiment of the Omnidirectional 3D Camera.~~ Fig. 5 shows an omnidirectional stereo camera according to one exemplary embodiment.

[0019] ~~Figure 6: Circular Variable Wavelength Filter (CVWF).~~ Fig. 6 illustrates a Circular Variable Wavelength Filter (CVWF).

[0020] ~~Figure 7: Omni-directional Rainbow Light Projection Using the OMNI-Mirror and CVWF~~ Fig. 7 illustrates omnidirectional light projection system according to one exemplary embodiment.

[0021] ~~Figure 8: Omnidirectional Structured Light 3D Camera~~ Fig. 8 illustrates an omnidirectional structured light 3D camera according to one exemplary embodiment.

~~Description of the Preferred Embodiments~~DETAILED DESCRIPTION

[0022] ~~To dramatically increase the~~ The field of view of an imaging system may be increased by ~~, we propose a somewhat unusual approach:~~ using a reflective surface ~~(i.e.,~~ such as a convex mirror~~)~~ with a properly designed surface profile. ~~The field of view of a video camera can be greatly increased by using reflective surface with properly designed~~

~~surface shapes.~~ The rear-view mirror in a car is a daily example of using reflective mirror to increase the FOV of a driver.

[0023] There are a number of surface profiles that can be used to produce omnidirectional FOV. ~~Figure~~ 3~~lists three examples: conic mirror, spherical mirror, and parabolic mirror.~~ Figs 3A-3C illustrate three examples. Fig. 3A illustrates a conic mirror (300-1), Fig. 3B illustrates a spherical mirror (300-2), and Fig. 3C illustrates a parabolic mirror (300-3). The optical geometry of these convex mirrors provides a simple and effective means to convert video camera's planar view into an omnidirectional view around the vertical axis of these mirrors, without using any moving part. This is accomplished by directing light rays (310, 320, 330) from the surrounding to a camera (340).

[0024] ~~At the first glance, it appears that the omnidirectional imaging task can be accomplished by using ANY convex mirror. Unfortunately, this is not the case. In reviewing some basic of image formation, we know that an~~ An image is a two dimensional pattern of brightness (or colors). A satisfactory imaging system ~~must~~ ~~preserve two~~ preserves ~~essential~~ such characteristics as:

(1) Geometric correspondence: There must be a one-to-one correspondence between pixels in an image and point in the scene.

(2) Single Viewpoint Constraint: Each pixel in the image corresponds to a particular viewing direction defined by a ray from that pixel on image plane through a "pinhole" (single viewing point).

~~[0025] Notice that, although the convex mirrors listed in Figure 3 can greatly increase the FOV, and may prove adequate for certain omnidirectional scene monitoring applications, they are not satisfactory imaging devices. These reflecting surfaces do not preserve the single viewpoint constraint (SVC). For a high quality omnidirectional imaging system, all the light rays coming in the omni imager head should have a single (virtual) viewing point.~~

~~Design of the Omni Mirror That Meets the SVC~~

[0026] ~~In this section, we will discuss a desirable convex mirror surface profile that satisfies the single viewpoint constraint: all the (extensions of) light rays reflected by the mirror must pass through a single (virtual) viewpoint. We call such a reflective mirror the OMNI mirror.~~ As discussed, the profiles illustrated Fig. 3 can greatly increase the FOV, and

may prove adequate for certain omnidirectional scene monitoring applications. The reflecting surfaces illustrated in Figs. 3A-3B do not preserve the single viewpoint constraint (SVC). For a high quality omnidirectional imaging system, all the light rays coming in the omni imager head should substantially share a single virtual viewing point. In contrast, the light ray extensions (350, 360, 370) do not share a single virtual viewpoint on a rotational axis (380) of the system.

[0027] A single viewpoint constraint shall be broadly understood to mean that all the extensions of light rays reflected by the mirror must pass through a single, albeit virtual, viewpoint. A reflective surface that meets this constraint and the one-to-one pixel correspondence constraint will be referred to as an omni-mirror for ease of reference. Accordingly, the omni-mirror (410) is then the solid of revolution obtained by sweeping the cross-section about an optical axis (380-1) of the omni-directional imaging assembly (400). The function of the omni-mirror (410) is to reflect all viewing rays (310-1, 320-1, and 330-1) to the video camera's viewing center or focal point (430) from the surface of physical objects in the field-of-view. This reflection is such that all the incident portions of the light rays (310-1, 320-1, and 330-1) that reflect off of the omni-mirror (410) have projections (350-1, 360-1, and 370-1) that extend toward a single virtual viewing point (440) at the focal center of the omni-mirror (410). In other words, the omni-mirror (410) effectively steers the viewing rays (310-1, 320-1, and 330-1) such that the camera (420) equivalently sees the objects in the world from a single viewing point (440).

[0028] ~~Let us first define necessary symbols and terminology. As shown in the Figure 4, we use an off-the-shelf video camera with a regular lens whose FOV covers entire surface of the OMNI-mirror. Since the optical design of camera and lens is rotationally symmetric, all we need to determine is the cross-section function z(r) that defines the mirror surface cross section profile. The mirror is then the solid of revolution obtained by sweeping the cross-section about the optical axis. The function of the omni-mirror is to reflect all viewing rays coming from video camera's viewing center (focal point, labeled as C) to the surface of physical objects in the field-of-view. The key feature of this reflection is that all such reflected rays must have a projection towards a single virtual viewing point at mirror's focal center, labeled as O. In other words, the mirror should effectively steer viewing rays such that the camera equivalently sees the objects in the world from a single viewpoint O.~~ Fig. 4 illustrates an omni-directional imaging assembly (400) that includes an omni-mirror

(410) and an imaging device such as a video camera (420). The video camera (420) may be any suitable video camera, such as an off-the-shelf video camera with a regular lens with a FOV that covers substantially the entire surface of the omni-mirror (410). Off-the-shelf video cameras and lenses are rotationally symmetric. As a result, the cross-section function z(r) that defines the mirror surface cross section profile remains as the undetermined variable.

[0029] ~~We choose hyperboloid as the desirable shape of the Omni-mirrors. A well-know feature of a hyperbolic curve is that: the extension of any ray reflected by the hyperbolic curve originated from one of its focal points passes through its another focal point. If we choose the hyperbolic profile for the OMNI-mirror, and place a video camera at its focal point C, as shown in Figure 4, the imaging system will have a single viewpoint at its another focal point O, as if the video camera were placed at the virtual viewing location O.~~ Fig. 4 illustrates a hyperboloid as shape of the omni-mirror (410). A well-know feature of a hyperbolic curve is that the extensions (350-1, 360-1, and 370-1) of any ray (310-1, 320-1, and 330-1) reflected by the hyperbolic curve originated from one of its focal points passes through its other focal point. If we choose the hyperbolic profile for the omni-mirror such that all the extensions (350-1, 360-1, and 370-1) pass through one focal point at the viewing point (440), and place the focal point (430) of a video camera (420) at the other focal point of the hyperbolic curve, as shown in Figure 4, the imaging assembly (400) will have a single virtual viewpoint (440) as if the video camera (420) were placed at the virtual viewing location (440).

[0030] For any ~~moving parts. The field of view of a conventional camera or a light projector can be dramatically increased by employing a reflective mirror properly placed~~point P in ~~front of~~ the ~~camera or the projector. A pair of omnidirectional cameras is able to form a unique stereo imaging system that is able to obtain three dimensional images of surrounding~~ scene, the image reflected from the omni-mirror (410) to image sensor's image plane (470) has the radius of d_c:

$$d_c = \sqrt{u^2 + v^2} \qquad (2)$$

where u (450) and v (460) are the pixel indexes on the image plane (470). As shown in Figure 4, the camera viewing angle γ_c (480) corresponding to the point on the scene is given by:

$$\gamma_c = \tan^{-1}\frac{d_c}{f_c} \qquad (3)$$

The incoming light rays z (350-1, 360-1, and 370-1) to the camera can be described by a line equation:

$$z = \frac{r}{\tan\gamma_c} - f \qquad (4)$$

Omitting details of mathematical derivation based on the ~~OMNI Mirror~~omni-mirror equation (1), we can obtain a simple closed-form relationship between the omnidirectional viewing angle α (490) and ~~CCD~~the camera's viewing angle γ_c (480):

$$\alpha = \tan^{-1}\frac{2bc - (b^2 + c^2)\cos\gamma_c}{a^2 \sin\gamma_c} \qquad (5)$$

[0031] This equation establishes a one-to-one corresponding relationship between α and γ_c. This relationship is important when we perform triangulation calculation in the omnidirectional 3D camera system.

~~**First Embodiment: Omnidirectional Stereo Camera (OSC)**~~

[0032] ~~With a pair of the omnidirectional cameras, we can easily construct an omnidirectional stereo camera. Figure~~Fig. 5 shows a possible configuration of the ~~OSC.~~omnidirectional stereo camera (500). Two omni-mirrors (410-1, 410-2) are placed face-to-face ~~with~~and share a common optical ~~axes aligned. The~~axis (510). Two virtual imaging centers~~, O_1 and O_2,~~ (440-1, 440-2) are separated by a distance ~~of~~ (B), which forms the baseline for the stereo vision.

[0033] The triangulation can be carried out directly from omnidirectional images without the need for image conversion. Once a 3D object (520) is detected~~ in the omnidirectional image~~, the viewing angle γ_1 (480-1) and ~~γ_2~~ (480-2) can be determined from ~~cameras'~~ the geometry~~.~~ of the two cameras (420-1, 420-2). Based on equation (5), the virtual

viewing angles ~~of this 3D object, α_1~~α_1 (490-1) and ~~α_2, from~~ α_2 (490-2) between the 3D object (520) and the virtual ~~viewpoint O_1 and O_2~~viewpoints (440-1, 440-2) can be determined. The distance between one of the ~~viewing center~~virtual viewpoint (440-1, 440-2) and the 3D object (520) in the scene cane be calculated using straight forward triangulation principles:

$$R = \frac{\cos(\alpha_2)}{\sin(\alpha_1 + \alpha_2)} B \qquad (6)$$

where R is the Range, i.e. distance between ~~P~~a point in space, such as one on the 3D object (520) and ~~O.sub.~~the virtual viewpoints (440-1~~,~~, 440-2).

[0034] ~~**Second Embodiment: Omnidirectional Structured Light 3D Camera**~~ In other implementations (not shown) an improved imaging apparatus for generating a two dimensional image, includes a substantially hyperbolic reflective mirror configured to satisfy an optical single viewpoint constraint for reflecting a scene, an image sensor responsive to the reflective mirror and that generates two dimensional image data signals, and a controller coupled to the image sensor to control a display of two dimensional object scenes corresponding to said image data signals.

~~**[0035]** 4.5.1 Projecting Structured Illumination Using the OMNI Mirror Circular Variable Wavelength Filter (CVWF)~~

[0036] ~~Notice that in our Omni 3D camera system,~~Fig. 6 illustrates a circular variable wavelength filter (CVWF~~) is~~, 600) which may be used to facilitate the generation of 360° projection illumination through a convex mirror. The CVWF (600) is a circular optical glass plate coated with color rings of gradually varying wavelengths within the visible (400-700 nm) or IR (>700nm) region. The wavelengths of the coated color rings are linearly proportional to their ~~radians~~radii as measured from the center of the filter glass, plus an offset. For example, if the range is to be between 400-700 nm, the wavelength in the center of the CVWF would be 400, and would vary linearly with the radius to 700 nm, based on the radius of the CVWF. This feature provides a simple and elegant way of generating structured light for an entire scene without using any moving parts~~ (Figure 6).~~.

[0037] As seen in Fig. 6, the CVWF (600) may be used with a white light projector (610) to produce conical sheets of light (620, 630) of varying wavelengths. The

wavelength of the light λ passing through a particular position of the CVWF (600) is a linear function of r, the ~~radians~~radius measured from the center of the filter glass:

$$\lambda(r) = \lambda_c + \frac{(\lambda_o - \lambda_c)}{R} r \tag{7}$$

where λ_c, λ_o and R are filter parameters: λ_c is the wavelength corresponding to the filter's "center" (lowest wavelength color the filter can generate). λ_o is the wavelength corresponding to the filter's "edge" (highest wavelength color the filter can generate). R is the effective radian of the filter's "edge". And r is the ~~radians~~radius measured from the center of the filter glass.

~~[0038]~~ If the relative position of the CVWF (600) is fixed with respect to the white light projector (610), the projected light with the same wavelength forms light sheets of circular conic shapes. (620, 630). The cone angle ~~θ~~(640) between the light sheet and the normal line of the projector (650) is directly related to the wavelength of the light. In other words, the wavelength of the light is encoded with the geometric information of the projected ~~corn~~cone angle. ~~This fixed wavelength λ to angle θ relationship is the key idea for our~~ In order to obtain a rainbow~~3D camera system.~~

~~**Omni-directional Rainbow Light Projection Using the OMNI Mirror**~~

[0039] ~~In order to obtain a Rainbow~~-like illumination with a 360° omnidirectional projecting angle, ~~we use~~ an ~~Omni-Mirror~~omni-mirror (410; Fig. 4) may be used to reflect ~~the~~ ~~conic~~conical-shaped light sheets (620, 630) generated by the white light projector and a CVWF.

[0040] As shown in Fig~~ure~~. 7, ~~the~~ an omnidirectional rainbow light projection system (700) has a 360° effective projecting angle around the vertical axis (710) of ~~the OMNI~~ an omni-mirror ~~.~~ (410).

[0041] The ~~OMNI Mirror~~omni-mirror mapping provides an easy and elegant way to determine the onmni-projecting angle θ (720) of ~~a~~ conic light ~~sheet~~sheets (620-1, 630-1) based on the projection angle γ (730) of the white light projector ~~(WLP) γ~~ 610). The projection line equation is given by:

$$z = \frac{r}{\tan\gamma} - f \qquad (8)$$

Combining with the ~~OMNI Mirror~~omni-mirror equation yields:

$$\frac{(z-c)^2}{b^2} - \frac{r^2}{a^2} = 1, \quad where \quad c = \sqrt{a^2 + b^2} \qquad (9)$$

the reflecting point (740), which is characterized by the coordinates (r_{mp} , Z_{mp}) on the omni-mirror (410), can be calculated by solving a quadratic equation. Using some properties of the ~~OMNI Mirror~~omni-mirror (410) and simplification procedures in mathematical manipulations, the relationship between the white light projection angle γ (730), and the omni-projection angle θ (720) can then be expressed as:

$$\theta = \tan^{-1} \frac{2bc - (b^2 + c^2)\cos\gamma}{a^2 \sin\gamma} \qquad (10)$$

In other words, knowing the white light projection angle γ (730) and parameters of the ~~OMNI Mirror~~omni-mirror (410), the omni-projection angle θ (720), which is taken with respect to the virtual projection center (750), is fully determined. Since the value of γ (730) determines the projected wavelength in the rainbow spectrum λ, spatial geometric characteristics of the projected cone shape ~~Rainbow~~rainbow light ~~sheet~~sheets (610-1, 620-1) are fully defined. Although the 3D range calculation of the ~~Omni-~~3D camera does not require the precise relationship between θ and λ, such a concise relationship facilitates a simple design, implementation and tests of the omnidirectional rainbow light projector~~.~~ (700).

~~**Omnidirectional Structured Light 3D Camera**~~

[0042] ~~Figure~~Fig. 8 shows an embodiment of an omni-directional structured light 3D ~~camera.~~imaging system (800). An omnidirectional rainbow light projector (700) is used ~~herein~~ to produce a spatially varying wavelength illumination in the surrounding scene. An omnidirectional ~~camera~~imaging assembly (400) is placed co-axially (i.e., with optical axes aligned) with the omni-directional rainbow light projector~~.~~ (700). The virtual projection

centers~~, O_1~~, (740), and the virtual imaging center ~~O_2~~(440), are separated by a distance ~~of~~ ~~B~~(B'), which forms the baseline for the triangulation based 3D vision system. The triangulation can be carried out directly from the omnidirectional images without the need for image conversion. Once a 3D object (520-1) is detected in the omnidirectional image, the viewing angle ~~γ_2~~(480-3) is determined from cameras' geometry. The projection angle ~~γ_1~~(730-1) is determined from the wavelength of the structured light projection, due to the one-to-one corresponding relationship of the ~~Rainbow~~omnidirectional rainbow light projector (700) between the wavelength and the projection angle. The distance between the virtual imaging center ~~O_2~~(440) and the surface points on the 3D object in the scene can be calculated using straight forward triangulation principle:

$$R = \frac{\cos(\alpha_2)}{\sin(\alpha_1 + \alpha_2)} B \tag{11}$$

where α_1 corresponds to the omnidirectional viewing angle (490-3) and α_2 corresponds to the projection angle (720-1).

[0043] Accordingly, an omnidirectional rainbow light projector and an omnidirectional imaging system may be used together to quickly obtain images with known three-dimensional characteristics about view angle of 360 degrees. The preceding description has been presented only to illustrate and describe embodiments of invention. It is not intended to be exhaustive or to limit the invention to any precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be defined by the following claims.

~~The invention claimed is:~~ WHAT IS CLAIMED IS:

1. An omnidirectional two dimensional imaging apparatus comprising:

(a) A truncated convex reflective mirror that reflects an image of substantially hemispherical scene;

(b) An imaging sensor means positioned to receive said omnidirectional images;

whereby images with wide field-of-view of substantially hemispherical scene from a single viewpoint can be obtained.

2. An apparatus as recited in claim 1, wherein the reflective mirror is a substantially hyperbolic reflective mirror whereby the substantially hemispherical omnidirectional images with single viewing center can be obtained.

3. An omnidirectional stereo camera apparatus comprising of a pair of optically aligned omnidirectional two dimensional imaging systems as recited in claim 1 whereby the stereo omnidirectional images can be obtained.

4. An omnidirectional stereo camera apparatus comprising of a pair of optically aligned omnidirectional two dimensional imaging systems as recited in claim 2 whereby the stereo omnidirectional images can be obtained.

5. An omnidirectional three dimensional camera apparatus comprising:

(a) An omnidirectional two dimensional imaging systems as recited in claim 1;

(b) An omnidirectional structured light projection means;

whereby the three dimensional measurement of the surrounding objects in the omnidirectional scene can be obtained.

6. An omnidirectional three dimensional camera apparatus comprising:

(c) An omnidirectional two dimensional imaging systems as recited in claim 2;

(d) An omnidirectional structured light projection means;

whereby the three dimensional measurement of the surrounding objects in the omnidirectional scene can be obtained.

7. An improved imaging apparatus for generating a two dimensional image, comprising:

a substantially hyperbolic reflective mirror configured to satisfy an optical single viewpoint constraint for reflecting a scene;

an image sensor responsive to said reflective mirror and that generates two dimensional image data signals; and a controller coupled to ~~the~~said image sensor to control a display of two dimensional object scenes corresponding to said image data signals.

8. The improved imaging apparatus of claim 7, wherein ~~said~~ hemispherical image data signals generated by said sensor are projected from a single virtual viewingpoint at the focal center of said hyperbolic mirror.

9. The improved imaging apparatus of claim 7, wherein said substantially hyperbolic reflective mirror is a substantially convex mirror and wherein said image data signals generated by said image sensor ~~means~~ are projected from a single virtual viewing point at the focal center of said convex mirror.

10. An omnidirectional stereo imaging system,comprising:

a first camera that generates hemispherical image data signals;

a first substantially hyperbolic reflective mirror optically associated with said first signal generator such that said first camera views objects in an entire hemispherical field of view from a single virtual viewpoint at the focal center of said first reflective mirror;

a second camera that generates a second set of hemispherical image data signals;

a second substantially hyperbolic reflective mirror optically associated with said second camera such that said camera views objects in an entire hemispherical field of view from a single virtual viewpoint at the focal center of said second reflective mirror; and

a data generator responsive to said hemispherical image data signals from said first and second camera for generating three-dimensional data for objects in said hemispherical fields of view of said first and second reflective mirror.

11. The system of claim 10, wherein said first and second cameras point in opposite directions.

12. The system of claim 10, wherein image data signals correspond to acquiring a field of view simultaneously covering 360 degrees of viewing angle.

13. The system of claim 10, wherein a focal center of said first camera and said first hyperbolic reflective mirror are at focal points of a parabolic curve.

14. The system of claim 13, wherein a focal center of said second camera and said second hyperbolic reflective mirror are at focal points of a second parabolic curve.

15. The system of claim 14, wherein said parabolic curve and said second parabolic curve are substantially similar.

16. An omnidirectional two dimensional imaging system, comprising:

a reflective surface configured to reflect light rays such that extensions of said light rays are substantially coincident on a single viewing point; and

an imaging system configured to cover the entire surface of said omni-mirror.

17. The system of claim 16, wherein said reflective surface comprises a substantially hyperbolic mirror.

18. The system of claim 17, wherein said hyperbolic mirror first and second focal points in which said single viewing point is at said first focal point and a focal point of said imaging system is at said second focal point.

19. The system of claim 17, wherein said imaging system comprises a camera.

20. The system of claim 16, wherein said imaging system is configured to capture an image through a 360 degree viewing angle.

21. An omnidirectional stereo imaging system, comprising:

a first omnidirectional imaging assembly having a first imaging device and a first omni-mirror wherein a viewing point of said omni-mirror and a focal point of said imaging device are disposed on focal points of a hyperbolic curve;

a second omnidirectional imaging assembly having a second imaging device and a second omni-mirror wherein a viewing point of said omni-mirror and a focal point of said imaging device are disposed on focal points of a hyperbolic curve

wherein focal centers of said first and second omni-mirrors and focal points of said first and second imaging devices are substantially coaxial; and

wherein said virtual viewing points are separated by a predetermined distance.

22. The system of claim 21, wherein said imaging systems comprise first and second cameras that generate hemispherical image data signals.

23. The system of claim 22, further comprising a data generator responsive to said hemispherical image data signals from said first and second imaging devices for generating three-dimensional data for objects in fields of view of said first and second omni-mirrors.

24. The system of claim 22, wherein said first omni-mirror comprises a substantially hyperbolic reflective mirror optically associated with said first imaging device such that said first imaging views objects through a 360 degree field of view from a first virtual viewpoint at a focal center of said first camera and said second omni-mirror comprises a second substantially hyperbolic reflective mirror optically associated with said second imaging device such that said second imaging device views objects in through a 360 degree field of view from a second virtual viewpoint at the focal center of said second reflective mirror.

25. The system of claim 21, wherein said first and second imaging devices comprise cameras.

ABSTRACT

An omnidirectional stereo imaging system includes a first omnidirectional imaging assembly having a first imaging device and a first omni-mirror, a second omnidirectional imaging assembly having a second imaging device and a second omni-mirror wherein focal centers of the first and second omni-mirrors and focal points of the first and second imaging devices are substantially coaxial and the virtual viewing points are separated by a predetermined distance.

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~~Method and Apparatus for Omnidirectional Stereo Imaging~~

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~~[52] U.S. Cl 348/036;~~

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